

# Simulation of Long-Term Landscape-Level Fuel Treatment Effects on Large Wildfires

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**Abstract**—A simulation system was developed to explore how fuel treatments placed in random and optimal spatial patterns affect the growth and behavior of large fires when implemented at different rates over the course of five decades. The system consists of a forest/fuel dynamics simulation module (FVS), logic for deriving fuel model dynamics from FVS output, a spatial fuel treatment optimization program, and spatial fire growth and behavior model to evaluate the performance of the treatments in modifying large fires. Simulations were performed for three study areas: Sanders County in western Montana, the Stanislaus National Forest in California, and the Blue Mountains in eastern Oregon. Response variables reported here include: (1) fire size distributions, (2) large fire spread rates, and (3) burn probabilities, and all revealed the same trends. For different spatial treatment strategies, our results illustrate how the rate of fuel treatment (percentage of land area treated per decade) competes against the rates of fuel recovery to determine how fuel treatments accrue multi-decade cumulative impacts on the response variables. Using fuel treatment prescriptions that involve thinning and prescribed burning, even optimal treatment arrangements (designed to disrupt the growth of large fires) require at least 10% to 20% of the landscape to be treated each decade. Randomly arranged units with the same treatment prescriptions require about twice that rate to produce the same effectiveness. The results also show that the fuel treatment optimization tends to balance maintenance of previous units with treatment of new units. For example, with 20% landscape treatment, fewer than 5% of the units received 3 or more treatments in 5 decades with most being treated only once or twice and about 35% remaining untreated the entire planning period.

## Introduction

Benefits of fuel treatments for mitigating the severity of wildfires have been documented at the stand level for much of the 20<sup>th</sup> century (Weaver 1943, Cooper 1961, Biswell et al. 1973), particularly in ponderosa pine and dry mixed conifer forests in the western United States (ponderosa pine and Douglas-fir). Recent large wildfires have stimulated renewed interest in fuel treatments and prompted new studies that have confirmed these findings (Pollet and Omi 2002, Graham 2003, Graham et al. 2004, Raymond and Peterson 2005, Agee and Skinner 2005, Cram et al. 2006). Beyond the immediate stand level (i.e. fuel changes over time and large spatial scales) treatment effects are poorly understood. Only a few studies of treatment longevity exist (Biswell et al. 1973, van Wagtendonk and Sydoriak 1987, Finney et al. 2005) and indicate diminishing benefits beyond about a decade. Landscape-level effects from various treatment patterns are still largely theoretical (Finney 2001a, 2003, Hirsch et al. 2001) with few observations of

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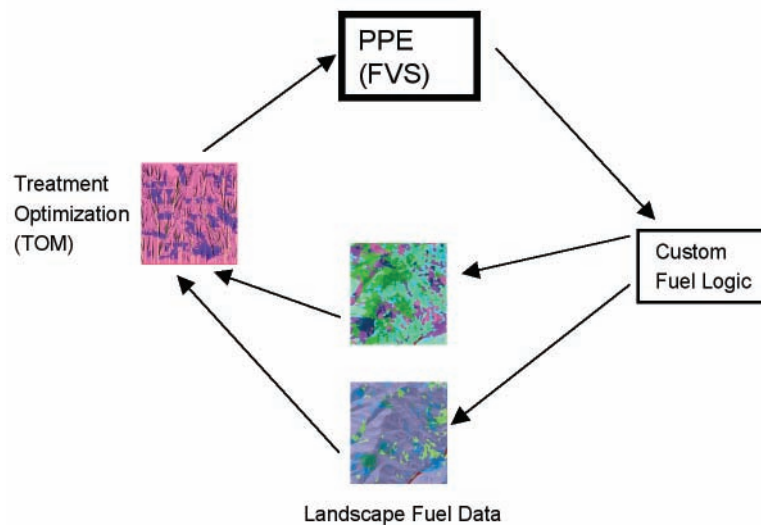
treatment performance in altering fire movement (Finney 2005). Given the difficulty with implementing large-scale and long-term experiments in fuel treatment, this study sought to use computer simulation to explore complex interactions of landscape treatment pattern and temporal vegetation/fuel changes in addressing the following questions:

1. What effect does spatial treatment pattern have on fire growth on complex landscapes?
2. At what rate must fuel treatments be implemented across a landscape to produce aggregated or cumulative effects on wildfire growth?
3. For purposes of disrupting fire growth, should existing fuel treatment units be maintained or should effort be made to implement new treatment units?
4. How do restrictions or constraints on fuel treatment location (because of conflicting land management objectives) affect treatment benefits?
5. How do landscape-level fuel treatment patterns perform under weather scenarios more moderate than the extreme conditions specified in their design?

## Methods

Our objectives were to produce a simulation system that implements fuel treatments over large landscapes in order to evaluate the impact on potential fire behavior over multiple decades. The system (Figure 1) consisted of:

1. The Forest Vegetation Simulator (FVS) for simulating the changes over time in forest vegetation (Crookston and Stage 1991) and fuels (Reinhardt and Crookston 2003). The FVS models were used for multiple stands comprising a landscape and for implementing the treatment prescriptions.



**Figure 1**—The simulation system was run for each decade. This system consisted of the Parallel Processing version of the Forest Vegetation Simulator (PPE-FVS) that simulated forest development with and without treatment, derivation of surface fuel models from the biomass categories and production of spatial landscapes for each scenario, spatial optimization of fuel treatment locations for disrupting fire growth, and implementation of treatments as feedback for the next simulation cycle in PPE-FVS.

2. A spatial model for choosing the location of treatment units using optimal or random selection logic (Finney 2002a, 2004, Finney in prep.).
3. A fire growth simulation model used to evaluate the impact of treatments in terms of fire growth rate, fire sizes, and relative burn probability (Finney 2002b).

## ***Simulating Forest and Fuel Conditions and Treatment Prescriptions using FVS***

The Forest Vegetation Simulator (FVS) is widely used in the U.S. for forest growth and yield modeling (Wykoff et al. 1982) and has recently been modified to record information on fuels and woody debris (Reinhardt and Crookston 2003). FVS has multiple “variants” that correspond to species, growth rates, and fuel types of forests in numerous regions throughout the U.S. Our system relied on a custom version of the Parallel Processing Extension (PPE) of FVS (Crookston and Stage 1991) which processes the stand list cycle-by-cycle (rather than one at a time for all cycles as in the normal version of FVS) and implements specific silvicultural and fuel treatment prescriptions (i.e. modifies forest and fuel structures). This custom version of PPE controls the simulation loop that calls separate routines outside of PPE that identify specific stands to treat. The PPE module then implements the prescriptions and processes the growth and fuel deposition for the next simulation cycle.

The stand-level prescriptions representing fuel treatments in FVS were specifically developed for treating fuels rather than to extract forest products (e.g. timber volume) or meet long-term ecological objectives. Treatments that include removal of surface fuels by prescribed burning have shown the greatest effectiveness in reducing fire intensity and severity (Helms 1979, Martin et al. 1989, Fernandes 2003, Raymond and Peterson 2005, Agee and Skinner 2005), either alone or in combination with silvicultural activities that reduce vertical and horizontal continuity of canopy fuels (Hirsch and Pengelly 1999, van Wagtenonk 1996, Stephens 1998, Graham et al. 1999, Agee et al. 2000, Cram et al. 2006). Canopy fuel parameters that influence crown fire include crown base height and canopy bulk density (Agee 1996, Scott and Reinhardt 2001, Agee and Skinner 2005). Treatments that only involve cutting or canopy manipulation without surface fuel mitigation were not implemented here because these activities often increase fuel availability (Alexander and Yancik 1977, van Wagtenonk 1996, Brown et al. 2004, Stephens and Moghaddas 2005, Raymond and Peterson 2005). Based on the precedence of modifying surface fuels whenever canopy fuels are manipulated, prescriptions were developed for each stand on the entire landscape based on the forest species composition, structural stage, and general understory fuel type (e.g. shrubs, grass, litter).

- Prescribed burning only. This prescription was used for maintenance of the surface fuels when there was no need to reduce aerial fuels. This prescription reduces surface fuels only and may kill small understory trees and regeneration using the mortality functions in FVS (Table 1).
- Prescribed burning after various harvest prescriptions (typically low-thinning). This treatment removes slash from the mechanical activities as well as the pre-existing surface fuels (Table 1).

FVS requires a “tree-list” to be supplied for each stand. A tree list contains the number of trees by species and stem-diameter class. FVS also requires initialization of dead and downed “fuel pools” which represent the current loading states of various fuel components and are critical to consequent fuel

**Table 1**—FVS treatment prescriptions were developed to work inside of FVS/PPE which provided a variety of general fuel treatments based on stand and fuel conditions at the beginning of each decade.

<b>Seedling/Sapling size class</b>
Thin from below to 1580 trees/ha (640 trees/acre) If 0 to 7.62cm diameter fuel loading (0-3 inch) $\geq$ 5.6Mg/ha (2.5 tons/acre) Pile and burn fuel treatment
<b>Poletimber size class</b>
For fire tolerant forest types (PP & DF) Thin from below to 30 m <sup>2</sup> /ha (130 ft <sup>2</sup> /ac) of basal area Prescribe burn
For fire intolerant forest types (all others) Thin from below to 34 m <sup>2</sup> /ha (150 ft <sup>2</sup> /ac) of basal area Pile and burn fuel treatment
<b>Sawtimber size class</b>
For lodgepole pine forest type Clearcut with reserves Prescribe burn
For fire tolerant forest types (PP, DF, WP, & WL) Thin from below to 32 m <sup>2</sup> /ha (140 ft <sup>2</sup> /ac) of basal area Prescribe burn
For fire intolerant forest types (all others) Thin from below to 34 m <sup>2</sup> /ha (150 ft <sup>2</sup> /ac). of basal area Pile and burn fuel treatment

dynamics. Since a landscape is composed of polygons that delineate individual stands, all stand polygons must be assigned a tree list. We used a process called Most Similar Neighbor (MSN, Crookston et al. 2002) that uses a representative sample of tree lists from areas throughout the landscape to input tree lists to polygons with no local measurements. The MSN process uses canonical correlation analysis, a multivariate technique, to select the tree list that corresponds to the polygon with minimum weighted distance of predictor variables. Tree lists for measured stands were obtained from existing data collected by a) local forest stand exams, and b) Forest Inventory and Analysis plots (FIA) (Van Deusen et al. 1999, McRoberts et al. 2000, Reams et al. 2001). The size of stand polygons was approximately the same for each study site, varying from 5 ha to 10 ha.

The output from the PPE version of FVS is contained in a table of stand conditions each year in the planning period (we used a period of 10 years). This table contains the fuel conditions that would have occurred with no treatment along with those that resulted from application of the treatment prescription that is critical for assessing the impact of the treatment on potential fire behavior. The fuel conditions specified are those required of the fire behavior models used to evaluate wildfire impacts (Finney 1998). The FVS polygon fuels data specifically includes canopy cover, stand height, crown base height, canopy bulk density, as well fuel pools, treatment history, and stand species information for assigning a fuel model (Anderson 1982, Scott and Burgan 2005). Because FVS currently does not utilize the Scott and Burgan surface fuel models, the fuel model assignment for each stand was accomplished outside of FVS-PPE. When the stand conditions are mapped

spatially to the polygon locations, a forest landscape can be constructed to contrast the effects of treatment for all stands in terms of fire behavior variables. Non-forested polygon fuel conditions (e.g. grass, rock) were held constant through the simulation.

### ***Spatial Locations of Fuel Treatments***

Having two sets of landscape fuel conditions each decade (depicting conditions with and without treatment) makes it possible to spatially delineate areas where fuel treatments are effective at changing stand-level fire behavior. Treatments were only considered possible for areas where fire behavior would be modified by implementing that prescription (e.g. thinning and prescribed burning of a particular stand could not be conducted in sequential decades if the second treatment did not reduce fire spread rate). Thus, the landscape configuration of areas suitable or available for fuel treatment would vary from decade to decade.

To move from the stand-level to the landscape-level, the spatial treatment optimization attempts to locate a specified percentage of these stands to treat, which optimally disrupt the growth or movement of large fires across that landscape (Finney 2002a, 2004, Finney in prep.). This optimization numerically implements the concepts described by Finney (2001a) for an optimal spatial arrangement of discrete units on a simple landscape that can be solved analytically. For complex real landscapes, a numerical technique is required, and makes use of a fire growth technique (Finney 2002b) to identify major travel paths produced by fires growing under a set of specified weather conditions. These weather conditions are obtained from historic local climatology associated with large and extreme fires.

The algorithm finds intersections between the fire travel paths and stands where the treatments slow the fire under the specified “target” weather conditions. Target weather conditions are synthesized for a particular study area from weather associated with historic large fires for which suppression is ineffective (Finney 2001a). Weather parameters include fuel moisture, wind speed and wind direction for the afternoon burning period (when the majority of fire area is burned). Typically, most large fires in a particular region have a similar orientation produced by the wind flow of a synoptic weather system that repeatedly contributes to the escape and rapid growth of fires. Thus, selecting these conditions ensures that treatment prescriptions modify fuels to sufficiently change fire behavior when fire suppression is impossible. Stands that slow the fire are identified by the contrast in fire behavior between treated and untreated stands. Fire behavior is calculated for each grid cell of each landscape using an implementation of fire behavior models described by (Finney 1998). Thus, a comparison of spread rate between two locations indicates where treatments reduce spread and can thereby contribute to retarding fire movement.

The spatial optimization technique begins by dividing the landscape into rectangular strips oriented normal to the predominant wind direction (Finney 2002a, 2004, Finney in prep.). Beginning with the strip farthest upwind, fire growth is simulated to identify major fire travel routes and their intersection with potential treatment areas (areas where the fire is slowed by the treatment). The process then iterates to delineate separate treatment units (one for each travel route) as constrained by unit size total treatment area. The orientation of the treatment units will typically be perpendicular to the major fire spread direction because this intercepts the main direction of fire movement. This procedure is followed for each strip moving successively in

the direction of the wind because treatments imposed on the landscape affect the downwind fire travel routes and subsequent treatment areas.

For purposes of comparison of the spatial optimization, the spatial fuel treatment module linked to PPE was enabled to perform a random selection of forest stands.

### ***Modeling Landscape-Effectiveness of Fuel Treatments***

The performance of the various fuel treatment patterns at each decade were evaluated in terms of the responses of fire growth (Finney 2002b) under the 99<sup>th</sup> percentile “target conditions. Effects of treatment are measured entirely assuming an absence of fire suppression because the weather conditions targeted for fuel treatment performance have historically been associated with large fires for which suppression efforts were ineffective (i.e. 99<sup>th</sup> percentile). However, reductions in overall fire growth rates, fire intensity, and fire sizes that would be expected to facilitate suppression action in treated areas and by linking or connecting treatment units by fire control lines (Bunnell 1998).

Wildfire responses were measured with the following metrics:

1. Total fire travel time (and thus, aggregated spread rate across the landscape) under the target weather conditions
2. The sizes of a randomly ignited fires on the landscapes, and
3. The average relative burn probability for all places on the landscape by randomly ignited fires.

The fire travel time was used to calculate the aggregated average fire spread rate of a fire from the upwind to the downwind edge of the landscape. This was performed by igniting the upwind edge of the landscape and running the simulation until it arrived at the downwind edge. The fire size distributions were obtained from simulations of 3,000 randomly located fires across each landscape. These fires were simulated for the same weather conditions identified as the “target” conditions used for the optimization because the fires targeted for treatment performance are those that escape initial attack efforts. This assumes that fire management policies attempt to suppress all fires, leaving to spread only those that cannot be controlled under extreme weather conditions (Table 2). The simulated fires are used to estimate the relative burn probability for the landscape which is derived by tallying the total number of fires that cross each grid cell of the landscape.

### ***Study Areas and Simulation Scenarios***

A large number of scenarios were developed for simulating five decades of vegetation dynamics and treatment activity. The main variables evaluated were:

1. Treatment amount (e.g. proportion of the landscape, from 0 to 50%),
2. Maximum treatment unit size (400 to 1600 meters per unit),
3. Treatment unit pattern (optimal vs. random),
4. Reserves of randomly selected areas in the proportion of 15% to 65% of the landscape,
5. Fire simulations under weather percentiles of 90<sup>th</sup>, 95<sup>th</sup>, to test treatment performance designed at the 99<sup>th</sup> percentile.

The study areas were selected to represent some of the variability in forest conditions that exist in the western U.S. The study sites selected for modeling actual landscapes are based on data availability and differences in the fire regime, policy, land ownership, and social context. The variety of conditions

**Table 2**—Summary of study area attributes and fire weather conditions simulated for fuel treatment optimization.

Study Area, Location and size	Land Ownership	Fire Regimes (general severity classes)	Fire Weather conditions used for fire modeling
Blue Mountains, OR 54,600 ha	<ul style="list-style-type: none"> <li>• Wallowa-Whitman NF</li> <li>• Umatilla NF</li> <li>• Tribal (Umatilla)</li> <li>• Private (non-industrial)</li> <li>• Private (industrial)</li> </ul>	<ul style="list-style-type: none"> <li>• Low-Mixed Severity</li> </ul>	<ul style="list-style-type: none"> <li>• Wind 48kph, West</li> <li>• Fuel Moisture (1hr 3%, 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)</li> </ul>
Sanders County, MT 51,700 ha	<ul style="list-style-type: none"> <li>• Lolo NF</li> <li>• Kootenai NF</li> <li>• Private (non-industrial)</li> <li>• Private (industrial)</li> <li>• Salish and Kootenai Tribes</li> <li>• MT Department of Natural Resources &amp; Conservation</li> <li>• Sanders County, Montana•</li> </ul>	<ul style="list-style-type: none"> <li>• Low, Mixed, High</li> </ul>	<ul style="list-style-type: none"> <li>• Wind 48kph, West</li> <li>• 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)</li> </ul>
Stanislaus NF, CA 40,500 ha	<ul style="list-style-type: none"> <li>• Stanislaus National Forest</li> <li>• Private (non-industrial)</li> <li>• Private (industrial)</li> </ul>	<ul style="list-style-type: none"> <li>• Currently Mixed-High, but historically low-mixed.</li> </ul>	<ul style="list-style-type: none"> <li>• Wind 48kph, West</li> <li>• 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)</li> </ul>

at these sites is intended for comparison of how fuel management objectives (specific in both space and time) can be accomplished in the context of realistic variability, constraints on management activities, and understanding of fire weather conditions. Table 2 contains the fire weather conditions used for each study area associated with 99<sup>th</sup> percentile Energy Release Component (ERC) from the U.S. National Fire Danger Rating System (Deeming et al. 1977).

**Sanders County, Montana**—Sanders County consists of 680,000 ha in western Montana along the Idaho border from which a study area of 51,700 ha was selected (Figure 2, Table 2). Land ownership is about 65% National Forest, 10% Plum Creek Timberlands, 5% school trust lands administrated by the Montana Department of Natural Resources and Conservation, and 20% small private landowners. Topography consists of the Bitterroot Mountains with the Flathead and Clark Fork Rivers flowing the length of the county. A wide variety of fuel types are present, with sagebrush/grasslands at the lower elevations in the eastern half of the county, frequent fire interval ponderosa pine (*Pinus ponderosa*) stands throughout, western red cedar (*Thuja plicata*) stands at the west end of the county and lodgepole (*Pinus contorta*) and whitebark pine (*Pinus albicaulis*) stands perpetuated by stand replacement fires at higher elevations. Private lands with the associated towns and improvements are concentrated in the lower elevations along the rivers and consist of the flashier fuel types. Barriers to fuel treatment include habitat concerns for a variety of endangered species; grizzly bear, wolves, lynx, and bull trout. Other issues are water quality limited streams and checkerboard ownership.



**Figure 2**—The study areas were located in western Montana (Prospect, Sanders County), the Sierra Nevada mountains of California (Stanislaus National Forest), and eastern Oregon (Mill Creek).

Data for the study area of Sanders County, Montana consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The polygon coverage was derived from that used in the Northern Region Vegetation Mapping Project (Brewer 2004). Data from USDA Forest Service Forest Inventory and Analysis (FIA) and Salish-Kootenai Tribe Continuous Stand Inventory (CSI) plots (commonly referred to as stand exam, forest inventory data, or observations) were used to create tree lists. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using nearest neighbor analysis, resulting in all forested polygons having a tree list attributed.

Two sub-areas were chosen from Sanders County (labeled Prospect and Baldy) because of the large size of the County and varying forest types and treatment options. The Prospect area represents the north Idaho forest types such as western hemlock (*Tsuga heterophylla*) and true firs (*Abies* spp.), limited past management activities, continuous dense forest cover, prevalent brush fuels beneath the forest canopy, and predominance of National Forest ownership. The Baldy landscape was smaller and more variable than Prospect. It contained a large rocky area at high elevation surrounded by drier forest

types including ponderosa pine and Douglas-fir and was composed of lands administered by Indian tribal governments (Salish and Kootenai tribes) and U.S. National Forest. Significant past management activities have created a variety of age classes, forest structures, surface and aerial fuel conditions.

**Stanislaus National Forest, California**—The Stanislaus National Forest is 363,000 ha and lies in the heart of the central Sierra Nevada from which 40,500 ha was selected for simulation (Figure 2, Table 2) with 7,754 tree-list polygons. The administrative boundary includes industrial private timberlands and small private parcels, many of which have been developed for housing. Vegetation varies from hard chaparral (*manzanita* species), oak (*Quercus* species) woodlands and ponderosa-pine (*Pinus ponderosa*) stands at the lower elevations to the west to mixed-conifer and red fir (*Abies magnifica*) forest at middle and upper elevations to the east. The western edges of this area are representative of the wildland-urban intermix of the Sierra Nevada foothills. The fire management strategy for the area was outlined recently in the forest plan amendment Record of Decision. This directs the forests in the Sierra Nevada to reduce threats to urban intermix areas and maintain 30 to 40% of the landscape in strategically placed treatments. Treatment effectiveness, landscape design, and monitoring effectiveness are key implementation questions. The fire regime has changed from a predominantly surface fire regime among all forest type prior to settlement to more of a mixed-high severity fire regime since about 100 years of fire exclusion. Surface and crown fuels on all lands now contribute to a relatively continuous fuel complex with the potential for broad destruction and loss of life if a fire should occur under extreme conditions. The foothills of the central and northern Sierra Nevada have recently been prone to these kinds of fires and result in losses and costs in the hundreds of millions of dollars.

Data for the California study area consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The Pacific Southwest Region Vegetation Inventory Strata map was used for the polygon coverage. USDA Forest Service, Forest Inventory and Analysis (FIA) data, supplemented with additional plots in rare types and plantations, were used for the tree lists. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using most-similar-neighbor analysis, resulting in all forested polygons having a tree list attributed.

**Mill Creek, Oregon**—The Mill Creek study area consists of 256,780 ha of federal and privately owned lands situated southeast of Walla Walla, WA. (Figure 2, Table 2). A subset of this area (54,600 ha) was used for the simulations with a total of 5,732 different stand polygons simulated. The entire area is situated on the west slope of the Blue Mountains, bordered by agricultural lands on the west and the USFS wilderness on the east. The private lands are located on the western edge. About half of the study area is forested with the remaining area covered by a mixture of dry grasslands, wet meadows, and shrubs. Elevations range between 500 m along the lower western edge to over 1,800 m in the east. The forest composition follows elevation, with dry forests of ponderosa pine (*Pinus ponderosa*) intermixed with grasslands in the west, cold forests dominated by subalpine-fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) in the east, and a transition zone containing grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*) in the mid elevations.

Forest stand delineations on the Forest Service portion of the study area were obtained from existing vegetation GIS layers on file at the Umatilla National Forest. Vegetation data and fuel loadings for these stands were obtained from the Umatilla National Forest vegetation database. Tree lists were a mix of field exams and data obtained from nearest neighbor analysis. Stands outside the Forest Service boundary were digitized on orthophotos flown in year 2000, and vegetation and fuels data obtained by field surveys. Photo series including Fischer (1981) were used to estimate initial surface fuel loadings.

We simulated stand-level treatments that consisted of selective thinning from below, mechanical fuels treatment, and underburning. The thinning prescription used the stand density index (SDI), and we triggered a thin in FVS when a stand's SDI exceeded 65% of the maximum SDI as specified in Cochran and others (1994). The thinning prescriptions targeted removal of late-seral, fire intolerant species like grand fir in mixed-species stands, favoring early seral species such as ponderosa pine, western larch and Douglas-fir. We simulated site removal of fuels and underburning after thinning.

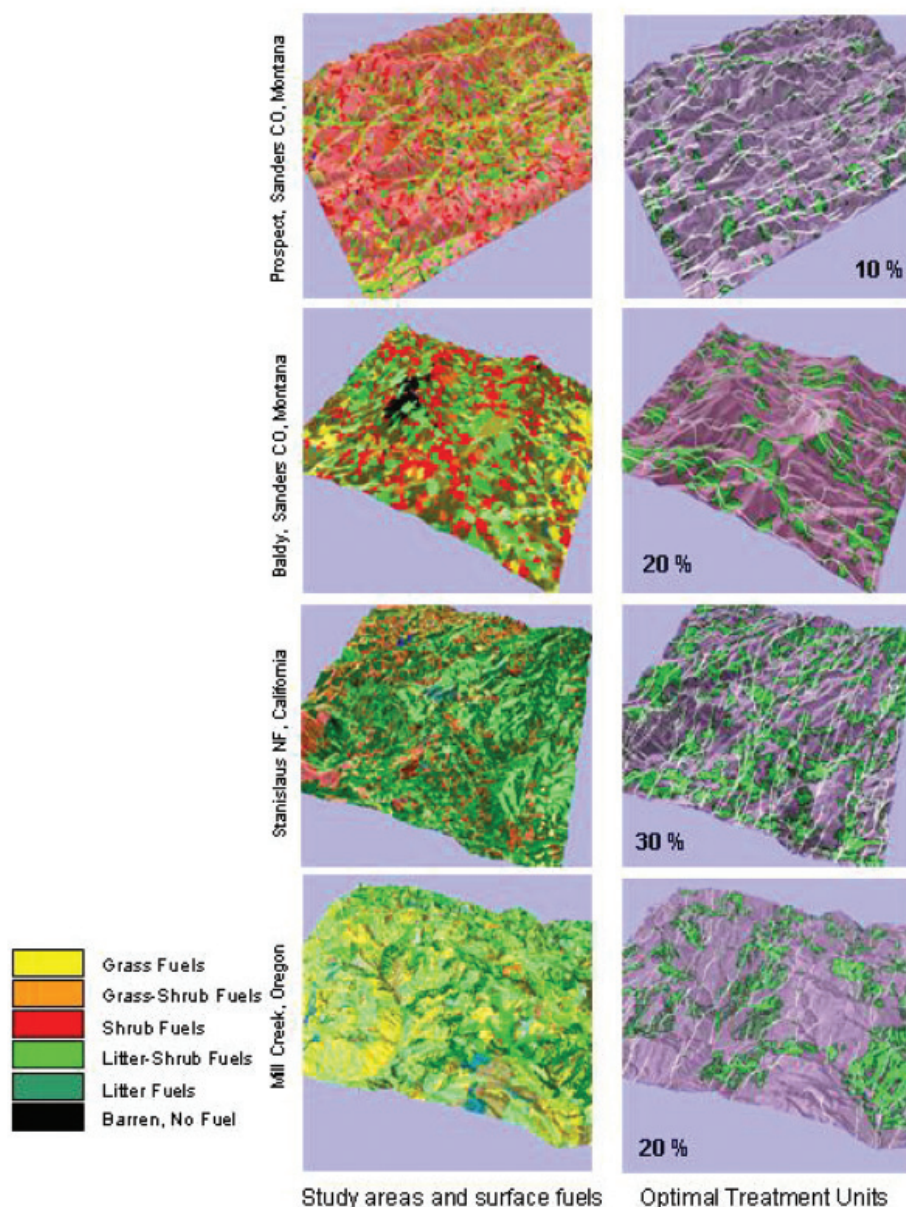
## Results

The simulation system was designed for multi-processor computers because of the intensive nature of the treatment optimization program and fire growth model. The fire growth algorithms (Finney 2002a) and the treatment optimization module were the most intensive and were run on 16-processor systems. Run times for five decades of simulation ranged from 6 hours to several days depending on the size of the landscape (area and number of cells) and the resolution of the treatments. Treatment units were identified by the treatment optimization (Figure 3) for each landscape for the target weather conditions.

The performance of the treatments was measured in terms of the change in landscape-level fire behavior, including average spread rate, conditional burn probabilities, and average fire sizes. All measures showed identical responses to the treatments (Figure 4) because slower moving fires burning for a specified period of time will be smaller and thus contribute to a lower overall probability of burning any portion of the landscape. Thus, only the relative spread rate is reported for the remaining simulation results. All measures revealed that the landscape fuel conditions, and thus fire behavior, were changing over time even in the absence of treatment (top line in all graphs on Figure 4). The treatment effects must be evaluated with respect to the untreated condition at each decade.

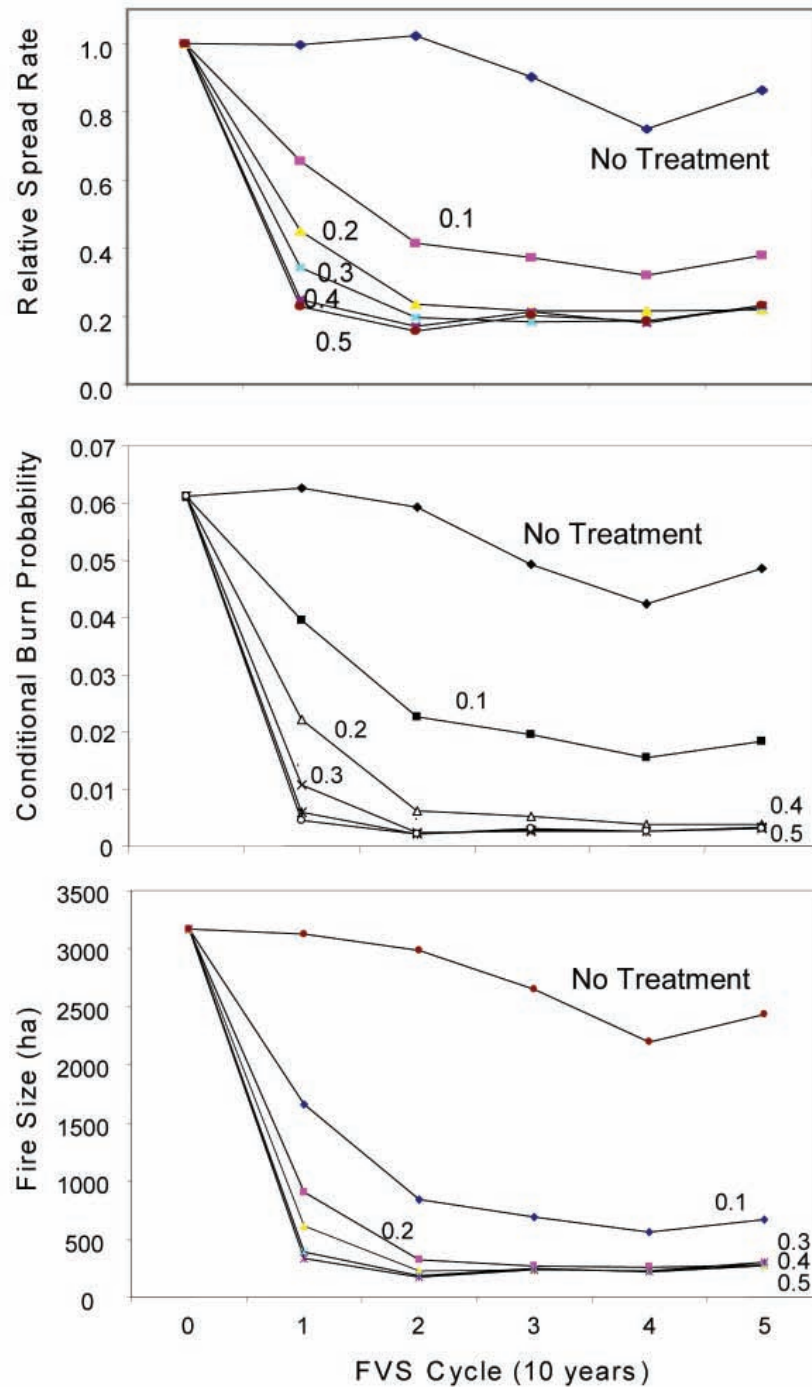
Optimal patterns of treatment units were found to reduce the average fire spread rate efficiently for all study areas in comparison to random patterns (Figure 5). Treatment unit size varied from 400 m to 1,600 m but unit size had little influence on the effect of optimal treatment patterns on fire spread rate regardless of the rate of treatment, simulation time, or study area (Figure 5). The Baldy study size (Sanders County, Montana) showed the greatest variation of relative spread rate (Figure 5f) in relation to treatment sizes from 200 m to 1,600 m, especially as the percentage of area treated increased.

For each study area, the average fire spread rate decreased with percentage of treatment but the amount of reduction varied by study area (Figure 5). Treatments were found to be more efficient for the Prospect study site in Montana than for any of the other study areas (Figure 5). With 10% treatment per

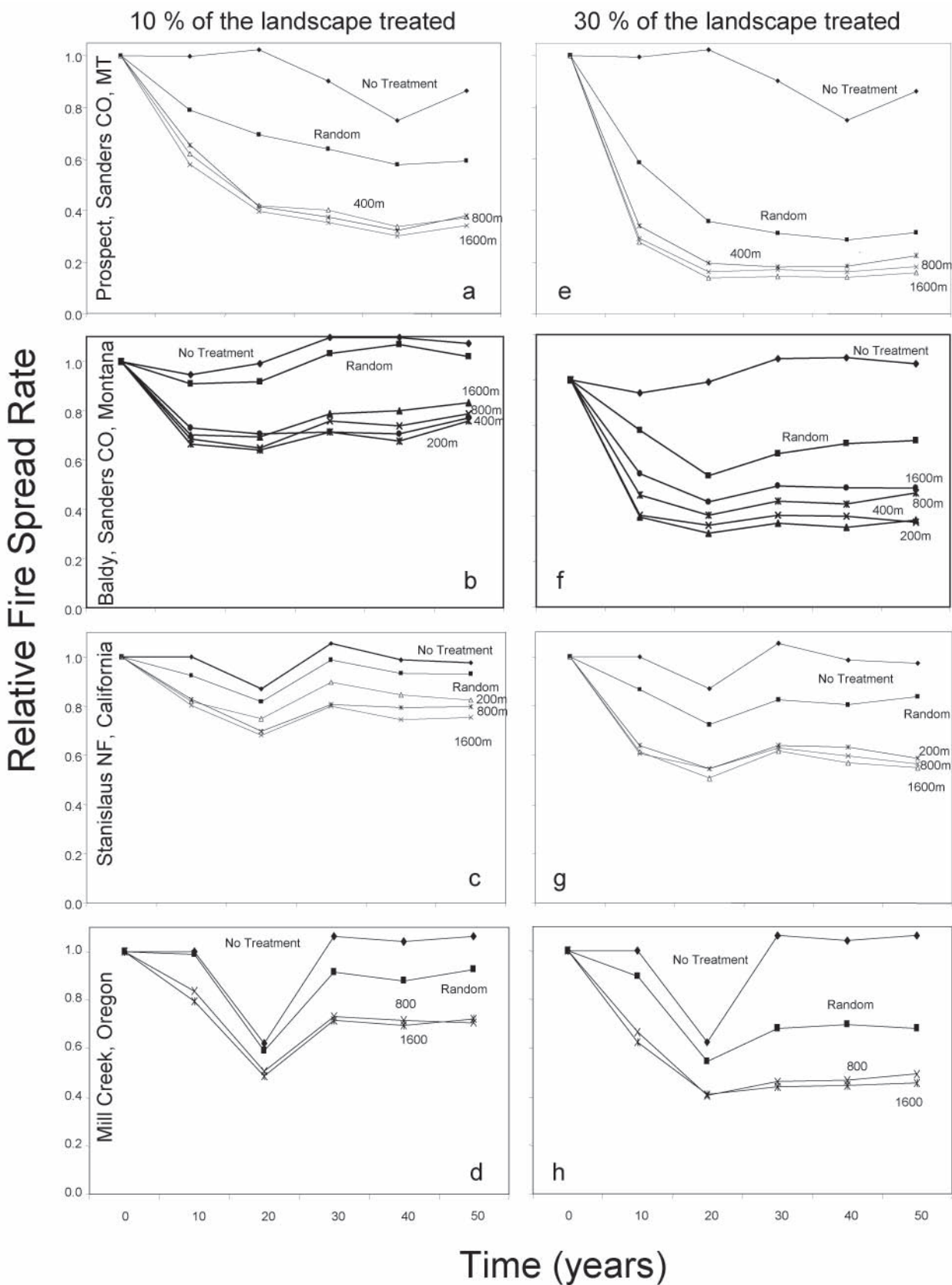


**Figure 3**—Example data and outputs from the Montana, California, and Oregon study areas showing surface fuel types and examples of optimized treatment locations along with major fire travel routes prior to placement of treatment locations (treatment location are intersected by travel routes).

decade, the fire spread rate was reducing to about 40% at Prospect, Montana (Figure 5a), 60% at Baldy Montana (Figure 5b), and 80% in California (Figure 5c), and 60% in Oregon (Figure 5d). Increasing rate of treatment to 30% per decade improved the overall reduction in spread rate to 20% for Prospect, Montana (Figure 5e), 40% for Baldy Montana (Figure 5f), 60% for California (Figure 5g), and 40% for Oregon (Figure 5h). For all study areas and treatment rates the effects of treatment were the greatest the first decade and the cumulative effect of additional treatment was negligible after the second decade of simulation. These trends occurred irrespective of the amount of treatment but were more noticeable with high treatment rates.



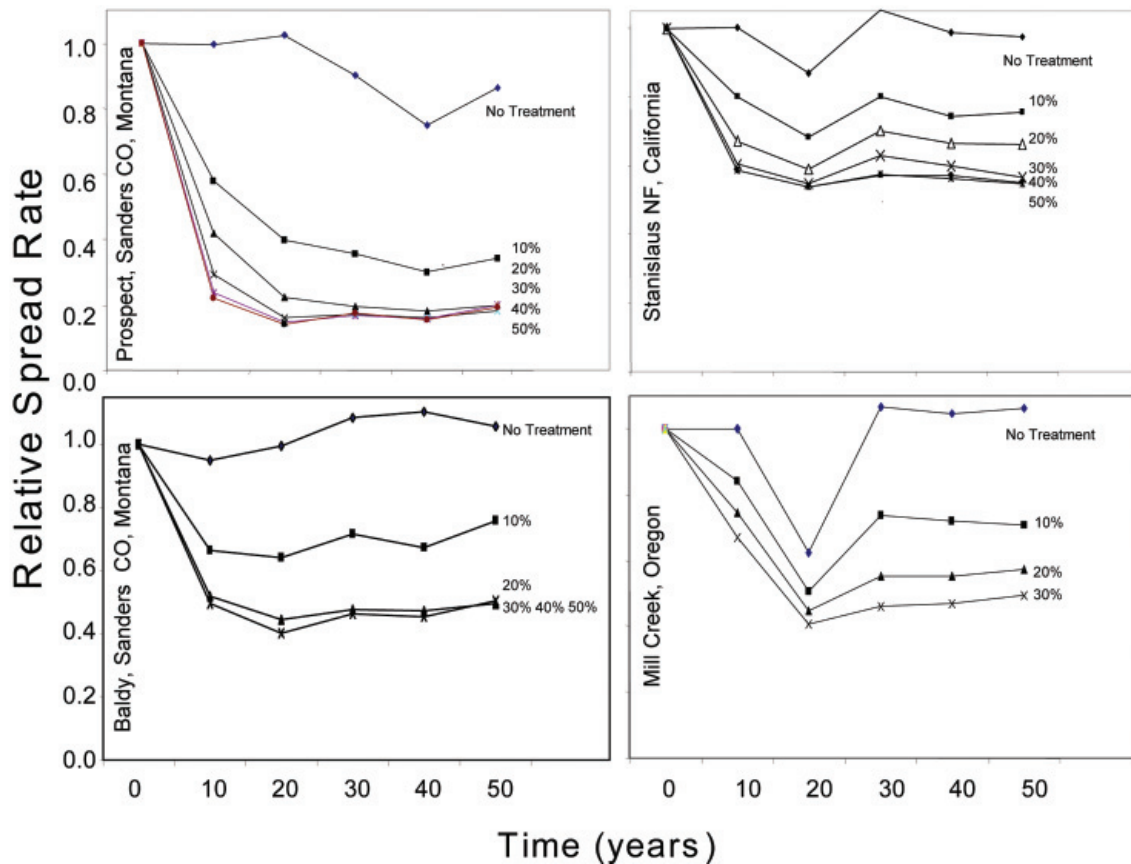
**Figure 4**—Average fire spread rate across the landscape, conditional probability of burning produced by simulating 3,000 fires (conditional upon having a large wildfire), and the mean fire sizes revealed nearly identical trends. Shown here are only the results for the Prospect, Montana study area, although all study areas had identical comparisons among the response variables.



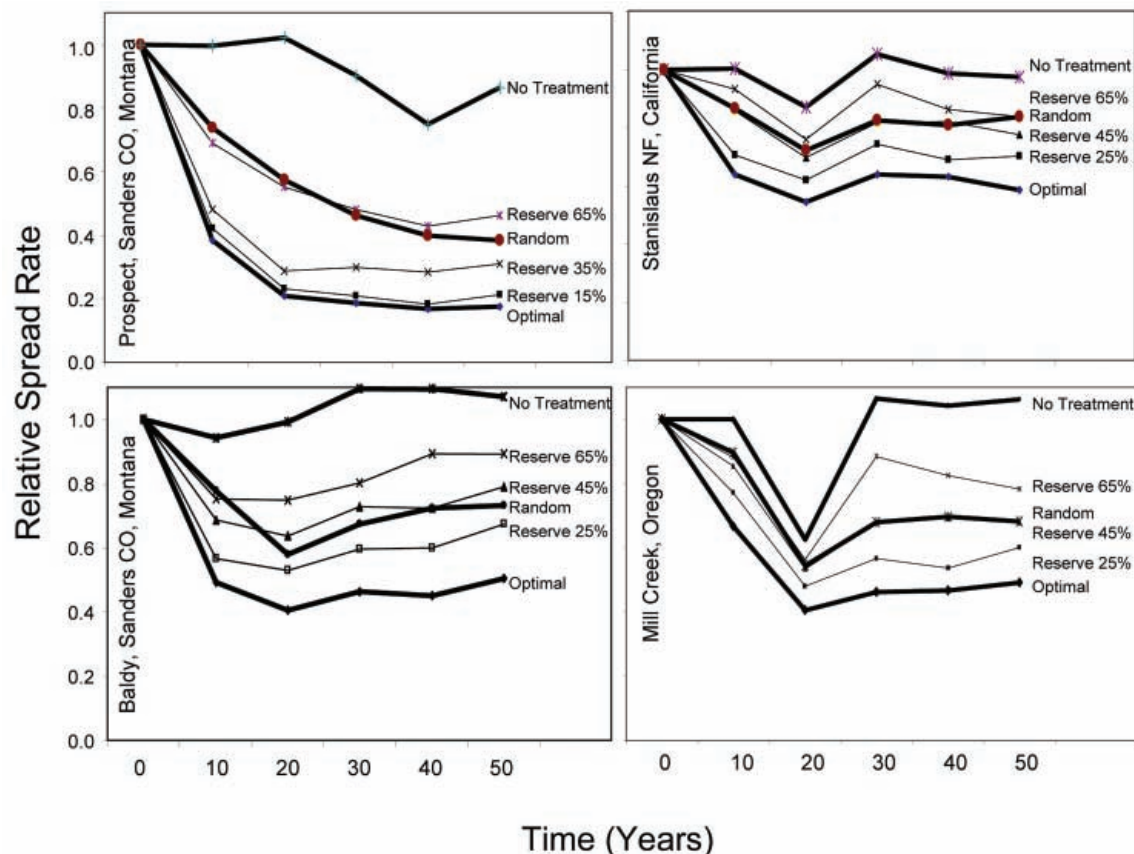
**Figure 5**—The magnitude of the treatment effect on average fire spread rate varied by study area although the cumulative effects over time of random and optimally placed treatments were similar for all areas. Treatment unit size had little effect on the average fire spread rate.

The rate of treatment in optimal patterns had a large effect on the cumulative treatment effectiveness up to approximately 20% per decade (2% per year) for all study areas (Figure 6). Increasing treatment rate beyond this point had little effect on the ultimate fire spread rates. For each rate of treatment (1% to 3% per year), the results suggested that cumulative effects of the optimal patterns reached a steady state after the second decade (Figure 6) as well as for random treatment patterns (Figure 5). Higher rates of treatment (40% to 50% per decade) produced little cumulative benefit to landscape fire spread beyond the first decade.

Effectiveness of optimal treatment patterns in reducing fire spread rate was little affected by randomly reserving less than about 20% of the area from consideration from treatment (Figure 7). However, reserving 45% to 65% of the area from treatment diminished the effectiveness of optimal patterns to about the level of random patterns.



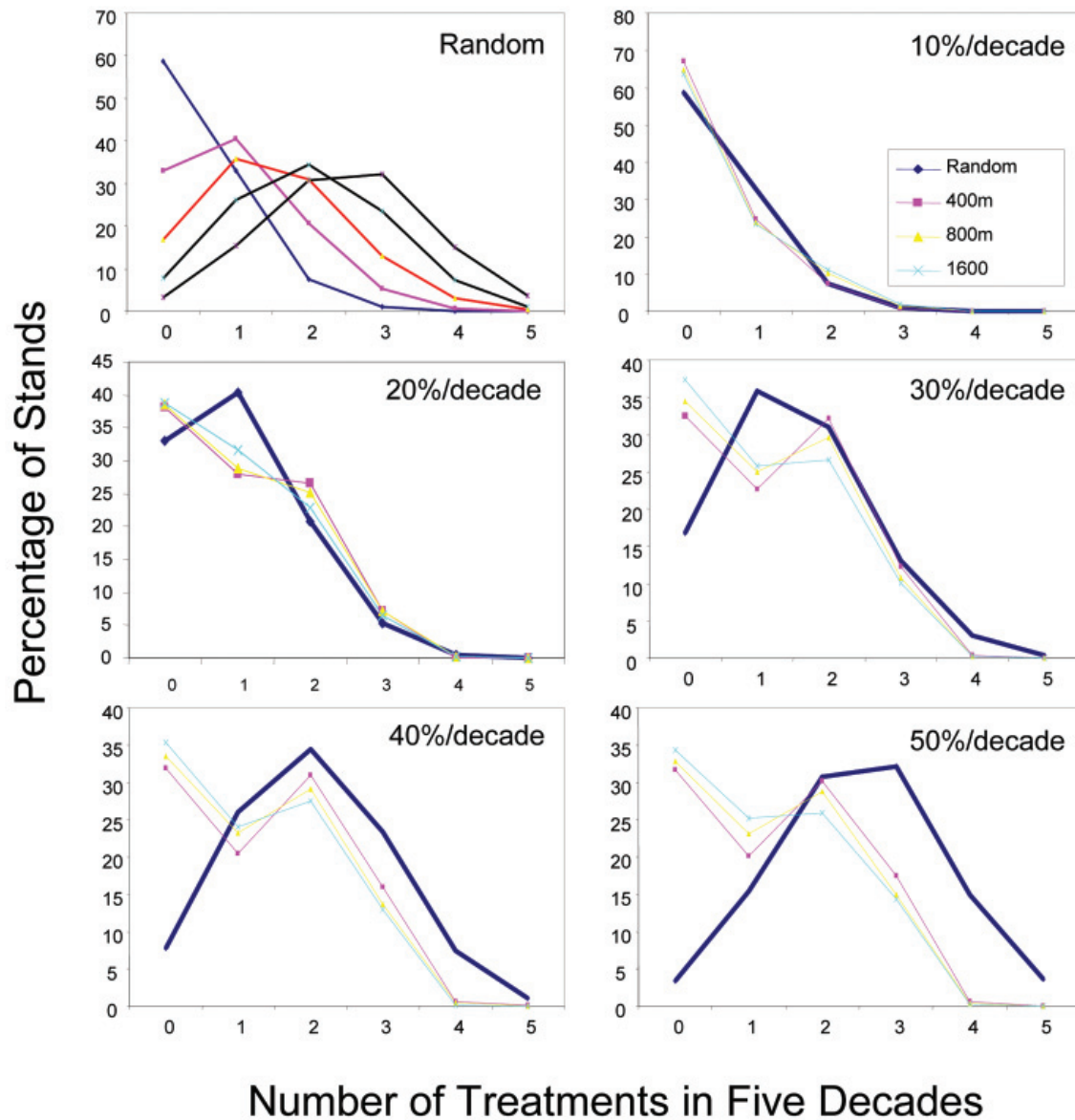
**Figure 6**—Treatments implemented at a rate of about 20% per decade produced overall reductions in average fire spread rate similar to higher treatment rates for all study areas. Treatment rates of up to 20% per decade required about two decades to reach the cumulative benefit reached in the first decade for higher rates of treatment. All results are displayed for 800 treatment units, but trends are nearly identical for unit sizes of 200 m, 400 m and 1,600 m.



**Figure 7**—Simulated reserves of land area from fuel treatment reduced the effectiveness of optimal treatment patterns to the point that reserving 45% to 65% produced results similar or even less effective than random patterns.

The treatment preferences for re-treating or maintaining fuel conditions in the optimal patterns was increasingly different from a random pattern as the rate of treatment increased beyond 10% (Figure 8). The trends were so similar for study areas that only the Prospect, Montana results are shown in Figure 8. The random treatments produced the expected Poisson distributions of treatment frequency (Figure 8a) which were similar to the treatment frequency produced for optimal patterns at a rate of 10% per decade (Figure 8b). However, treatment frequency was not random at higher rates of treatment in optimal patterns (Figures 8c-8f). Specifically, about 35% of the landscape would never be treated in an optimal pattern even with the highest rate of treatment (50% per decade). Where treatment rates were the highest (40% to 50% per decade), most fuel treatments were not maintained every decade (Figure 8e, 8f).

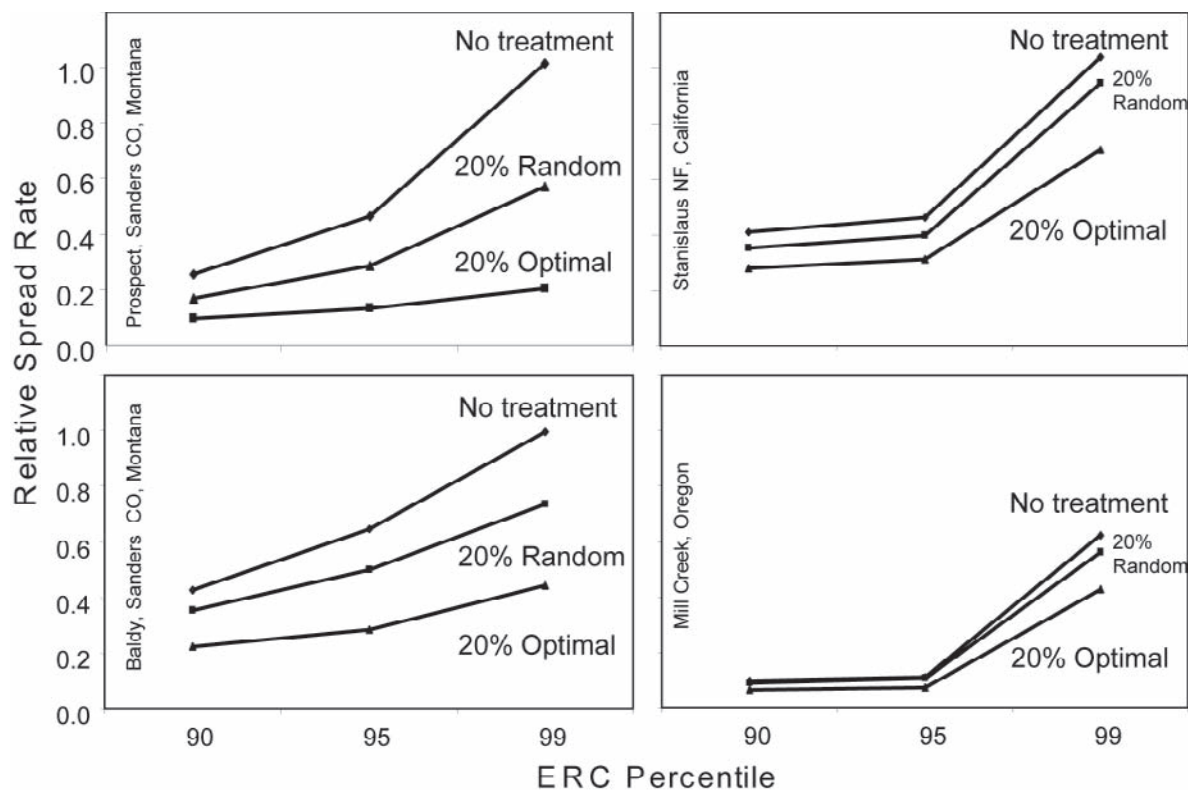
Optimal treatments in all study areas remained more effective than random treatments (Figure 9) in reducing fire growth rate under weather conditions more moderate (90<sup>th</sup> and 95<sup>th</sup> percentile) than specified in the design (99<sup>th</sup> percentile). The relative benefit of treatment, however, decreased as conditions became more moderate because fire behavior contrasts decrease between treated and untreated areas.



**Figure 8**—The question of maintaining treatment areas or implementing new treatments was summarized by the frequency of treatment over five decades. Random treatment resulted in Poisson frequency distributions. At treatment rates of 20% and greater per decade, the optimal treatment strategy consistently excluded some areas from treatment more frequently than random selection and refused frequent treatment for other areas.

## Discussion

The simulations for the three study areas consistently suggested that all treatment rates (10% to 50% per decade) accumulated benefits to reduced fire spread rate, wildfire sizes, and burn probability out to about two decades in all study areas. This is probably a result of the inherent fuel accumulation and decomposition rates which determine longevity of individual treatments. Beyond that point, additional treatments produced little cumulative reduction in the landscape fire metrics. Additionally, treatment rates beyond approximately



**Figure 9**—Comparison of fuel treatment effects on relative fire spread rate across a range of fire weather percentiles suggests that optimal treatment effects are robust under weather more moderate than the conditions specified for optimization (99<sup>th</sup> percentile). Spread rates are shown for the 2nd decade of simulation (when collective treatment effects are maximal) and normalized for each study area relative to the spread rate at the beginning of the simulation (i.e. zero years). Weather percentiles are expressed in terms of Energy Release Component (ERC) from the National Fire Danger Rating System and primarily reflect changes in moisture content.

20% per decade in optimal patterns produced little added benefit for the study areas. Few studies have directly measured fuel accumulation, but van Wagtenonk and Sydoriak (1987) found that litter and fine twigs returned to preburn levels in 5-7 years in the Sierra Nevada mountains of California. The results of this study are generally similar to the findings of Biswell et al. (1973), Fernandes et al. (2004), Finney et al. (2005) who reported fuel treatment mitigation of wildfire severity out to 15 years, 13 years, and 9 years, respectively. These timeframes for treatment longevity imply certain rates of treatment by land management planners, namely that a substantial level of effort is required over the course of about two decades to realize the cumulative benefits to mitigating large fire behaviors. Such effort has long been advocated as a critical part of overall fire management (Brackebusch 1973, Arno and Brown 1991). Evidence for effectiveness of such large scale-efforts were documented by Weaver (1957) and showed prescribed burning in eastern Washington State over 11 years, which covered about 6% of the landscape, reduced fire occurrence on the treated lands by 97% and area burned by 90% compared to the untreated areas. We did not study the trajectories of treatment benefit related to changing the treatment rate through time, but, since higher treatment rates certainly accelerated the production of benefits, higher rates might be desirable in the first decade followed by later decreases.

The three response variables of large fires (growth rate, fire sizes, burn probabilities) all showed identical trends in relation to fuel treatments. Fire growth rates (aggregated spread rate across the landscapes), mean fire size, and the burn probability all decreased as fuel treatment amounts increased, both for optimal and for random patterns. The explanation is straightforward, given that faster fires will produce larger fires in an equal amount of time; larger fires burn a larger fraction of the landscape each time and thereby increase the burn probability. This is useful information for landscape fuel treatment planning in the context of risk assessment (Miller et al. 2000, Priesler et al. 2004, Finney 2005) because burn probabilities are a main component of risk. Fuel treatments can be designed to decrease burn probability by considering both the treatment prescription at the stand level and the spatial arrangement of the stands at the landscape level.

Differences in the maximum reduction of fire spread rate were found among study areas for random and optimal treatment patterns, probably because of different fuel treatment prescriptions and the changes simulated by FVS in the forest structures for those geographic locations. Differences could also be a function of the particular spatial configurations of fuel types for each landscape because treatments that dictated the areas suitable for treatment. Both of these factors likely affect the outcome of the simulations because the differences among study areas were consistent regardless of the use of optimal or random spatial fuel treatment patterns. Thus, either rapid recovery of fuels after treatment or limited positions of candidate treatment areas would have similar effects on reducing overall effectiveness on the landscape-level fire metrics.

Despite the complexity of the landscapes studied here and the complexity of modeling required to characterize fuels, fires, and treatment units, these results of the optimal and random landscapes correspond well with those based on the theoretical analysis of simple landscapes (Finney 2001a,b, 2003). For spatially optimal patterns, increasing the treatment rate reduces fire spread rate and exhibits a negative-exponential-type shape. This was found for all study sites and treatment unit sizes, although the magnitude of the decrease depends on the particular landscape. This is interpreted to be the consequence of different patterns of fast- and slow-burning fuel types on the real landscapes that dictate the opportunities and impacts of the particular treatment units. The decrease in spread rate with increasing treatment amount arranged in random patterns did not exhibit the sigmoidal trend found from analysis of simple spatial landscapes (Finney 2003), however, the random pattern was much less efficient in reducing large fire spread than the optimal patterns. The inefficiency of random patterns is also verified by other theoretical studies (Loehle 2004, Bevers et al. 2004). Together, these results are useful for drawing general conclusions about the role of spatial treatment patterns on fire movement. The theoretical and spatially simple results apply quite well to the expected trends for treatments on actual landscapes.

The benefits of optimal treatment patterns appear to be robust to uncertainties in weather (wind speed and fuel moisture) as revealed for weather conditions more moderate than those for which the patterns were designed (Figure 9). Under moderate weather conditions, the contrast in fire behavior between treated and untreated areas is diminished (fire spread rate and intensity tend toward similar values). This means that the treatments will result in a smaller proportional reduction in fire area than under extreme conditions. However, the primary reason that treatments are not designed for moderate fire weather is that modern suppression policies do not permit

large wildland fires to spread when suppression organizations are generally successful in limiting fire spread. Thus, fire behavior is generally more benign, fire suppression more effective, and treatments less necessary for changing fire behavior when weather conditions are moderate.

The effects of reserving areas from treatment, irrespective of the location or need for treatment, decreased the effectiveness of an optimal treatment pattern and compromised the optimal solutions entirely at about 50% reserved. This has bearing on the treatment planning process in land management operations where restrictions are imposed for a variety of reasons, including concern for treatment impacts on wildlife habitat, restrictions on proximity to streams or rivers, road access, budget limitations, or ownership. These simulations generally suggest that treatment restrictions amounting to more than about 40% of a landscape would diminish any advantage an optimal solution would achieve over purely random treatment placement. The specific topology of the various fuels and restrictions for a particular landscape, however, would likely be different than this generalization. Nevertheless, if land managers intend to achieve reductions in large fires, collaboration with all concerned parties would likely be necessary to accommodate treatment locations to achieve landscape-level effects.

The five-decade simulations suggest that both maintenance of existing units and implementation of new units are important to the optimization of spatial treatment patterns. The frequency of re-treatment in the optimal landscape was different than produced by chance with the random treatments (Poisson distributed) which indicates that the choice of fuel treatment activity was driven by functional concerns. Compared to the random patterns, the optimization attempted more treatments on new stands than on re-treating old stands, probably because the treatment benefits endured for more than one decade. It is unknown how the pattern would change if the simulation were to have continued for 100 years, for example, that would have greatly exceeded the time-frame of treatment performance.

Variation in treatment unit sizes had the least impact on modifying large fires compared to treatment pattern and rate of treatment. Large and small units typically produced similar reductions in fire sizes, spread rates, and burn probabilities at all levels of treatment. Slightly lower efficiency (e.g. amount of reduced spread rate per unit treated) of the smallest treatment unit sizes for all study areas, however, suggests that emphasizing small units may restrict opportunities to block fire movement in some critical locations which require large units. That is, small units cannot effectively block the movement through large corridors where fire easily moves. The optimization algorithm used here is not flexible enough to effectively mix both small and large units.

## Conclusions

The simulations suggested that long-term treatment effects are primarily dependent on the rate of application of treatments and the spatial patterns of treatment units. Treatment rates of 10% to 30% per decade reached a cumulative maximum effectiveness in about two decades in all study areas. Higher rates of treatment did not improve the cumulative effects beyond the first decade. Random treatment patterns also produced cumulative effects on fire behavior but were less efficient than the optimized patterns, requiring about twice the area to be treated compared to optimal patterns.

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